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OBSERVATIONAL DETERMINATION OF THE RATE OF MAGNETIC HELICITY TRANSPORT THROUGH THE SOLAR SURFACE VIA THE HORIZONTAL MOTION OF FIELD LINE FOOTPOINTS

Jongchul Chae[1]
Department of Astronomy and Space Science, Chungnam National University, 220 Kung-dong,
Yusong-ku, Daejeon 305-764, South Korea; chae@cnu.ac.kr
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ABSTRACT

Magnetic helicity may be transported to the solar corona through the solar surface either via the passage of helical magnetic field lines from below or via the shuffling of footpoints of preexisting coronal field lines. In this Letter, we show how to *observationally* determine the rate of magnetic helicity transport via photospheric footpoint shuffling from a time series of line-of-sight magnetograms. Our approach is not confined to the previously known shear motions, such as differential rotation, but can be exploited to search for the possible existence of physically significant shear motions other than differential rotation. We have applied the method to a 40 hr run of high-resolution magnetograms of a small active region (NOAA Active Region 8011) taken by the Michelson Doppler Imager on board the *Solar and Heliospheric Observatory*. In this region, we find that the rate of magnetic helicity transport oscillates with periods of 1 to several hours. Our result suggests that the time-series analysis of the helicity transport rate might be a useful observational diagnostic for the role of photospheric flows in the evolution of coronal magnetic fields in solar active regions.

Subject headings: Sun: atmospheric motions — Sun: corona — Sun: magnetic fields — Sun: photosphere

1. INTRODUCTION

There has been increasing observational evidence that solar magnetic fields have helical structures in many regions. The overall twist of active region magnetic fields has been inferred from measurements of all the vector components of photospheric magnetic fields (Pevtsov & Canfield 1999) and coronal structures seen in X-ray images (Canfield & Pevtsov 1999). Studies of the morphology and motion of cool plasma have indicated that magnetic fields in solar filaments and coronal mass ejections may be also helically structured (Rust 1999; Chae 2000). Therefore, the helicity of magnetic fields appears to hold an important key to solar eruptions such as flares and coronal mass ejections.

Magnetic helicity is physically defined by $\int \boldsymbol{A} \cdot \boldsymbol{B}\, dV$ and measures the sum of linkage between all possible pairs of field lines (see Berger 1999 for the concept of magnetic helicity in space physics). It is a physically useful quantity since it is fairly well conserved in a closed volume where field lines never pass through the enclosing surface. Magnetic helicity of an open volume like the solar corona, however, may change at the presence of a nonzero velocity field on the boundary surface. Berger & Field (1984) derived the Poynting theorem for the helicity in an open volume:

$$\frac{dH}{dt} = \oint 2(\boldsymbol{B}\cdot\boldsymbol{A}_p)v_z\, dS + \oint -2(\boldsymbol{v}\cdot\boldsymbol{A}_p)B_z\, dS, \qquad (1)$$

where $\boldsymbol{A}_p$ is the vector potential of the potential field, which is uniquely specified by the observed flux distribution on the surface with the equations

$$\nabla\times\boldsymbol{A}_p\cdot\hat{\boldsymbol{z}} = B_z, \quad \nabla\cdot\boldsymbol{A}_p = 0, \quad \boldsymbol{A}_p\cdot\hat{\boldsymbol{z}} = 0. \qquad (2)$$

According to equation (1), the helicity of magnetic fields in an open volume may change either by the passage of helical field lines through the surface (the first term) or by the shuffling horizontal motion of field lines on the surface (the second term). In emerging flux regions, the first term may be important as has been observationally supported (Leka et al. 1996). The twist observed in an emerging flux tube may originate either from the dynamo process operating at the base of the convection zone or from the interaction of the rising flux tube with convection zone flow such as turbulent motion and differential rotation (see, e.g., Longcope et al. 1999). In other regions that do not show flux emergence, the first term may be negligible, and only the second term may be significant. This means that surface motions, including the surface differential rotation, may be another probable origin of the twist or magnetic helicity (van Ballegooijen 1999).

In the present Letter, we demonstrate that the second term of equation (1)—the rate of change of the helicity of coronal magnetic fields due to the horizontal motion of field lines on the surface—can be observationally determined from a time series of line-of-sight magnetograms. Our approach is contrasted with previous studies (e.g., DeVore 2000; Berger & Ruzmaikin 2000) since we use observational data in determining the surface motions as well as the flux distribution, so we do not assume any a priori velocity field or flux distribution. Welsch & Longcope (2000) and B. T. Welsch (2001, private communication) have also been developing a method for determining the rate of the helicity transport from observations. They model the photospheric magnetic flux as a finite number of discrete magnetic elements and determine all the mutual helicities and self-helicities of the system based on the spatial information of the velocity field. They applied the method to the quiet-Sun magnetic flux that is deformed by the differential rotation. Our approach is different from theirs in that we use equation (1) directly, without any modeling. While previous studies focused on the effect of differential rotation, the present study puts more emphasis on the possible existence of surface motions other than differential rotation and their possible role in accumulating the magnetic helicity of coronal magnetic fields.

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[1] Also at Big Bear Solar Observatory, New Jersey Institute of Technology, 40386 North Shore Lane, Big Bear City, CA 92314-9672.

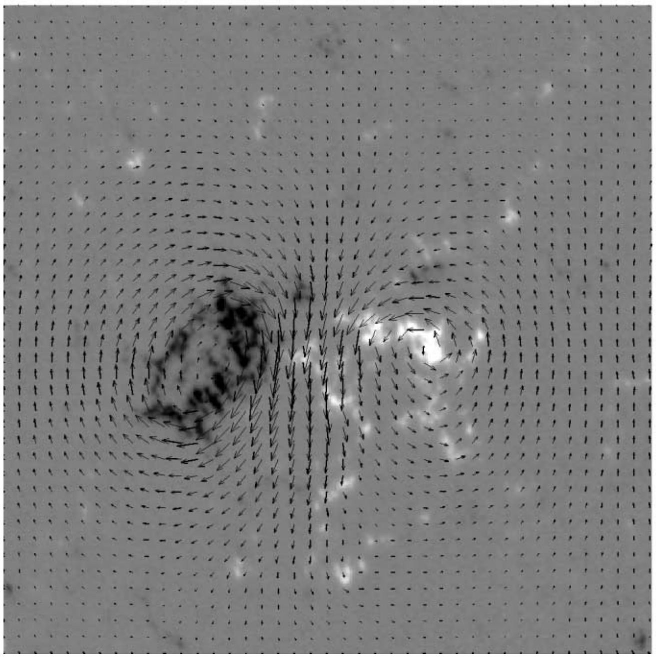

FIG. 1.—Gray-scale map of line-of-sight magnetic field and the superposed arrow map of the vector field $\boldsymbol{A}_p$ of NOAA AR 8011 at 17:00 UT of 1997 January 17.

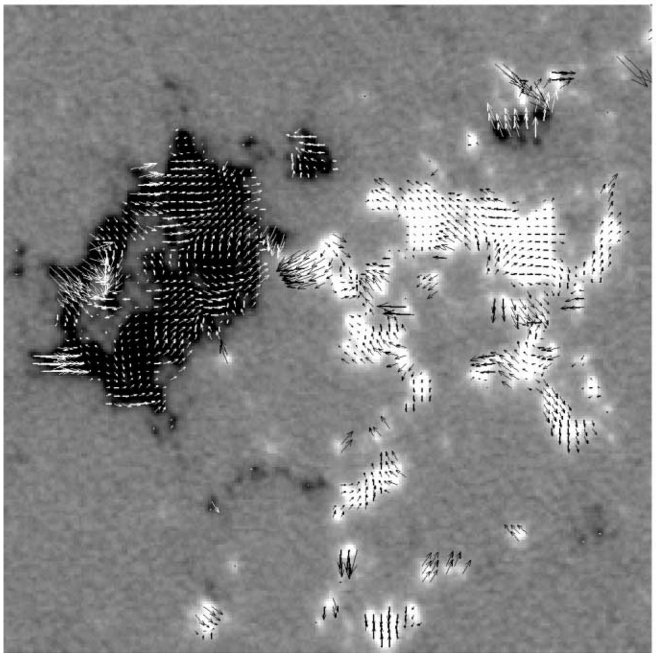

FIG. 2.—Arrow map of horizontal flow field

In the following discussion, we describe how to determine $\boldsymbol{A}_p$ and $\boldsymbol{v}$ from observations in an area using Cartesian geometry, and we apply this method to a 40 hr run of high-resolution magnetograms of a small active region (NOAA Active Region 8011) taken by the Michelson Doppler Imager (MDI; Scherrer et al. 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*; Domingo, Fleck, & Poland 1995). Chae et al. (2001) applied the same method to a bigger active region (NOAA AR 8668) and found that the magnetic helicity was being accumulated by a shearing motion on the surface while a filament was under formation.

2. METHOD AND RESULTS

We have aligned all the MDI magnetograms taken during the 40 hr observing run by applying the nonlinear mapping defined by the differential solar rotation (Howard, Harvey, & Forgach 1990). Therefore, the transverse velocities that are to be determined do not include differential rotation. Then we average every five successive magnetograms of 1 minute cadence in order to increase the signal-to-noise ratio. The gray-scale map in Figure 1 is an example of a magnetogram of the NOAA AR 8011 taken at a specific time (17:00 UT of 1997 January 17). This active region was the only one seen on the disk that day. The map has a field of view of 200″ × 200″ (145,000 × 145,000 km) and is exactly at the center of the solar disk. In this field of view, the line-of-sight magnetic field is practically the same as the vertical field.

We have calculated $\boldsymbol{A}_p$ from the observed vertical field distribution B_z using the Fourier solution of equations (2):

$$A_{p,x} = \mathrm{FT}^{-1}\left[\frac{jk_y}{k_x^2 + k_y^2}\mathrm{FT}(B_z)\right],$$

$$A_{p,y} = \mathrm{FT}^{-1}\left[-\frac{jk_x}{k_x^2 + k_y^2}\mathrm{FT}(B_z)\right], \qquad (3)$$

where a discrete Fourier transform of a function $A(x, y)$ is defined as

$$\mathrm{FT}(A) = \sum_{x,y} A(x, y) \exp(-jk_x x - jk_y y). \qquad (4)$$

This method is fast and easy to implement since it employs the fast Fourier transform. The arrow map in Figure 1 shows the horizontal vector field $\boldsymbol{A}_p$. The field has a clockwise rotation pattern in the negative magnetic flux region and a counterclockwise rotation pattern in the positive flux region. Moreover, the field is the strongest in the polarity reversal boundary between the two regions and runs parallel to the boundary.

We have determined the horizontal velocities of magnetic field lines at photospheric footpoints by measuring the local displacements of magnetic flux concentrations between two successive magnetograms with the technique of local correlation tracking (November & Simon 1988), which is a commonly used method. We have chosen 5″ for the FWHM of the apodizing window and 15 minutes for the time interval Δt between the two frames to be compared. To reduce the computing time, velocity vectors were determined only at the centers of macropixels with a size of 1″.5 × 1″.5 where the absolute value of the magnetic flux density is greater than 10 G. Figure 2 presents the horizontal flow vectors at the selected points. Note that, for a better display of details, only the central part of the observed field of view is shown in the figure. The rms value of the horizontal velocity vectors has been found to be about 0.15 km s^{-1}. At first sight, the distribution of horizontal flow vectors looks more or less random, and it is hard to find large-scale systematic flow patterns like twisting motion or shear motion. Nevertheless, we cannot exclude the possibility that the observed flows may contribute to the physically significant transport of the magnetic helicity through the solar surface.

An easy way to evaluate the physical significance of the observed flow on the magnetic helicity transport is to examine the spatial distribution of $-2(\boldsymbol{v} \cdot \boldsymbol{A}_p)B_z$, which is a measure of the local contribution of the footpoint motion to the rate of the magnetic helicity transport, as presented in Figure 3. The figure

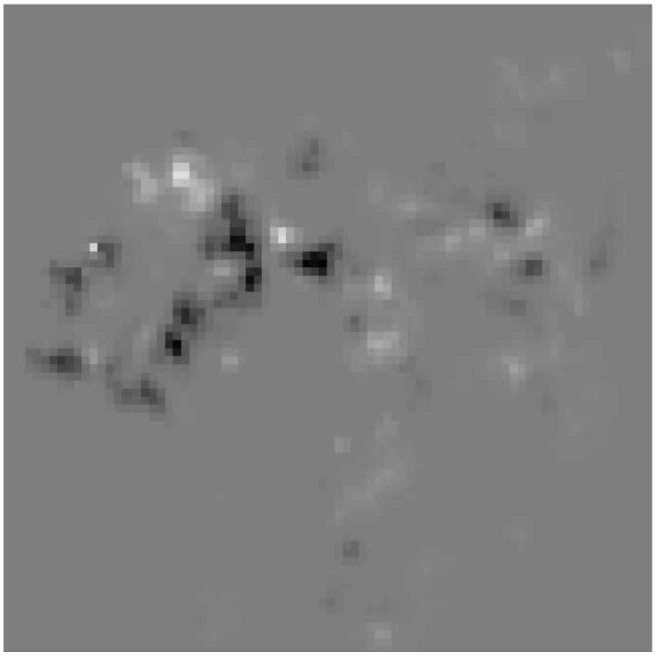

FIG. 3.—Gray-scale map of $-2(\boldsymbol{v}\cdot\boldsymbol{A}_p)B_z$

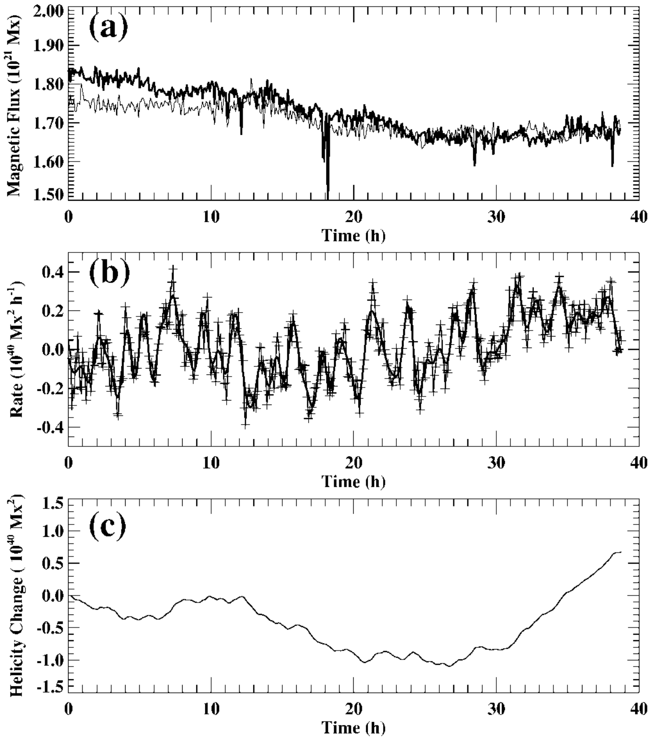

FIG. 4.—(*a*) Time variations of the integrated positive magnetic flux (*thick curve*) and negative flux (*thin curve*) of the observed region. (*b*) Measured helicity transport rate as a function of time (*plus signs and thin curves*) and its low-pass–filtered signal. (*c*) Accumulated change of the magnetic helicity due to the helicity transport as a function of time.

shows that $-2(\boldsymbol{v}\cdot\boldsymbol{A}_p)B_z$ is predominantly negative, indicating that its integration over the surface will produce a significant amount of the negative rate of the magnetic helicity transport. Comparing Figures 2 and 3 reveals that the major negative contributions came from shear motion near the polarity reversal boundary that is directed to the northwest in the negative polarity region and to the southeast in the positive polarity region.

The surface integration of $-2(\boldsymbol{v}\cdot\boldsymbol{A}_p)B_z$ is equal to $dH/dt = -0.4 \times 10^{40}$ Mx^2 hr^{-1}. If this rate would remain constant, the amount of helicity change would reach 10% of the square of the active region flux within 4 days. This is much shorter than the two to three solar rotation periods that are required to get the same amount of helicity change by solar differential rotation at high latitudes (DeVore 2000). But, unlike differential rotation, the observed shear motion exists only temporarily, being shorter lived than 1 hr. Therefore, for the proper evaluation of the accumulated effect of photospheric footpoint motion on the change of the magnetic helicity in the corona, it appears crucial to examine the time sequence of dH/dt with a good temporal resolution. The time sequence of dH/dt has been obtained by calculating $\boldsymbol{A}_p$ and $\boldsymbol{v}$ from the pair of magnetograms taken at each time and integrating $-2(\boldsymbol{v}\cdot\boldsymbol{A}_p)B_z$ over the surface.

Figure 4*a* shows the temporal variations of the integrated positive magnetic flux and the negative flux in AR 8011. The positive and negative fluxes are well balanced within 5% throughout the observing run, and fluxes of both polarities decreased with time, which is a natural characteristic of a decaying active region.

Figure 4*b* shows the temporal variation of dH/dt in AR 8011. The rate has been determined every 5 minutes for 40 hr. The prominent characteristic is that the rate fluctuates with a large amplitude of about 0.4×10^{40} Mx^2 hr^{-1}. This kind of large-amplitude fluctuation was also noticed in the study of Chae et al. (2001). They did not analyze the fluctuation in detail and therefore simply attributed it to the noise. But, in the present study, we see that most of the fluctuation is not due to noise in the measurements but is due to a low-frequency oscillation with periods longer than 1 hr. By selecting only the modes with periods longer than 1 hr, we have constructed the low-pass–filtered signal. The residual obtained by subtracting the low-pass signal from the time-series data comprises the measurement noise and the high-frequency fluctuation. The standard deviation of the residual is found to be 0.07×10^{40} Mx^2 hr^{-1}, which is about half of the standard deviation of the low-pass signal, 0.15×10^{40} Mx^2 hr^{-1}.

Figure 4*c* shows the accumulated change of the magnetic helicity that was obtained by integrating the measured dH/dt from the start of the observing run to the specified time. The temporal variation of $\Delta H(t)$ is mostly determined by the slowly varying modes of dH/dt. It went down to the negative peak of about -1.0×10^{40} Mx^2 in about 27 hr and then steadily increased to a positive value of 0.7×10^{40} Mx^2 for the next 12 hr. The average value of dH/dt is about -0.03×10^{40} Mx^2 hr^{-1} in the former phase and 0.14×10^{40} Mx^2 hr^{-1} in the latter phase.

It would be interesting to compare our result with previous studies. Berger & Ruzmaikin (2000) obtained 2×10^{41} Mx^2 hr^{-1} for an estimate of the rate of the helicity transport in a *hemisphere* by differential rotation. DeVore (2000) obtained a smaller value 1×10^{40} Mx^2 hr^{-1} for a *large bipolar magnetic region* with the flux of 1×10^{22} Mx that is located at latitude $b = 30°$. Note that our estimate of 1×10^{39} Mx^2 hr^{-1} has been obtained for a *small active region* near the disk center with a magnetic flux of 2×10^{21} Mx and that the observed surface motion is not differential rotation. Since the rate of helicity change depends on the magnetic flux and the location of the area of interest, a direct comparison of these different values would be meaningless. Therefore, for comparison, we make a new estimate of the rate of helicity change by differential rotation for the region of our study based on equation (15) of DeVore (2000): $dH/dt = \pi/32\Omega F^2$ with $\Omega = -8.6 \times 10^{-7} \sin b \cos^2 b$ s^{-1}. Using $F = 1.7 \times 10^{21}$ Mx and $b = -3°$ for our observing area results in $dH/dt = 4.5 \times 10^{37}$ Mx^2 hr^{-1}. This is very small, as expected for a region close to disk center, and is much smaller than our measurement. Therefore, we find that the rate of the magnetic helicity transport due to observed horizontal motion during our observing period is significantly higher than the contribution of differential rotation at the same latitude. Chae et al. (2001) studied NOAA AR 8668 with a magnetic flux of 10^{22} Mx centered at a latitude of 25° during a 2 day period when a filament was formed. They found a shear flow other than differential rotation that transported the magnetic helicity at a rate of 6×10^{40} Mx^2 hr^{-1}, which is also higher than the original DeVore (2000) estimate of 1×10^{40} Mx^2 hr^{-1}.

3. CONCLUSION

We have shown how to observationally determine the rate of change of the magnetic helicity of coronal magnetic fields, dH/dt, that is due to the helicity transport through the solar surface via the shuffling motion of photospheric footpoints. It has be emphasized that our approach is not confined to the previously well-known shear motions, such as differential rotation. As a specific result of applying the method to a small bipolar active region, NOAA AR 8011, we have found that the rate of the magnetic helicity transport via footpoint motion fluctuates with time and that its time sequence is characterized by the existence of long-period (≥1 hr) modes. We do not know if these oscillations are solar or instrumental in origin, and therefore more observational work definitely need to be done.

Our result suggests that the time-series analysis of the helicity transport rate might be a useful observational diagnostic for the role of photospheric flows in the evolution of coronal magnetic fields. We hope that this kind of study will eventually provide a way of monitoring the amount of the magnetic helicity of coronal magnetic fields and of predicting eruptions like coronal mass ejections. Coronal mass ejection is a process of transporting the mass, magnetic flux, and magnetic helicity out of the Sun. Its occurrence might be related to the accumulation of the magnetic helicity onto the corona by the helicity transport through the solar surface (Rust 1999).

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